Use of NRL P-3 and ELDORA in TPARC/TCS-08

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LONG-TERM GOALS

The long-term goals of this project are to understand better the mechanisms operative in tropical cyclogenesis and to transfer this knowledge to large-scale models in order to improve forecasts of tropical storm formation. Since convection constitutes the biggest uncertainty in this process, our focus is to understand how convection affects and is affected by cyclone-scale flows.

OBJECTIVES

Our objective in this segment of the program was to understand the vorticity budgets of developing and non-developing disturbances in the northwestern Pacific, including vorticity tendencies.

APPROACH

The TCS-08 field program provided a rich set of data including Eldora radar data and dropsondes from a variety of platforms. In order to be able to incorporate these results into a single product on which various analyses can be made, we developed a three-dimensional variational analysis (3-D Var) scheme. This scheme produces smooth analyses which strictly satisfy mass continuity, and which therefore provide a basis for computing vorticity and other higher order terms in the vorticity evolution equation. From this work we are able to compute or estimate all terms in the vorticity equation and therefore compute vorticity tendencies as residuals.

WORK COMPLETED

The 3D-Var analysis scheme, ng3dvar, has proven to be a robust and reliable analysis tool. It is now publicly available as part of our Candis (C-language ANalysis and DISplay) package at

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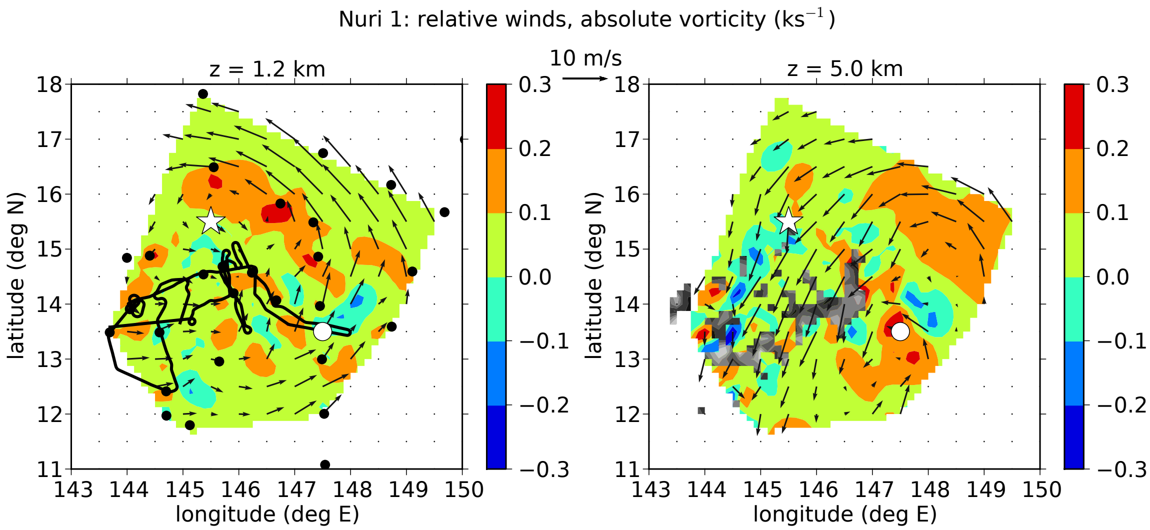

Figure 1: **Absolute vorticity (color levels) and storm-relative winds for Nuri mission 1 at 1.2 km (left panel) and 5 km (right panel). The black line and black dots in the left panel indicate the P-3 aircraft track and the locations of P-3 and WC-130J dropsondes. The gray scale insets in the right panel show regions of radar reflectivity exceeding 25 dBZ at 5 km. The white star and the white circle indicate the circulation centers in the PBL and at 5 km respectively. The white areas reflect the geometry of the mask chosen for this mission.**

http://www.physics.nmt.edu/~raymond/software/candis/candis.html,

and a paper describing it has been submitted (López and Raymond 2010).

We have used ng3dvar's output to make comprehensive analyses of the vorticity budget for the four case studies obtained on successive days of typhoon Nuri (2008) and its precursor disturbance. This work has also been submitted for publication (Raymond and López 2010).

Figure 1 shows the storm-relative winds and absolute vorticity in the first Nuri case study. Also shown are the NRL P-3 aircraft track and the locations of P-3 and WC-130J dropsondes in the left panel, and the regions of strong convection as a gray scale inset in the right panel. The white star and circle show respectively the storm-relative circulation centers at 1.2 km and 5 km elevation. These circulation centers are displaced from each other by approximately 3° in this case. The separation between these centers decreased to almost nothing as Nuri intensified.

Figure 2 shows the corresponding patterns for the non-developing tropical wave TCS030. As may be seen, there is no hint of a closed circulation at 5 km in this case. If the circulation at 1.2 km is closed, its center is well to the north of the observed region. There are thus no overlapping closed circulations through a deep layer in TCS030.

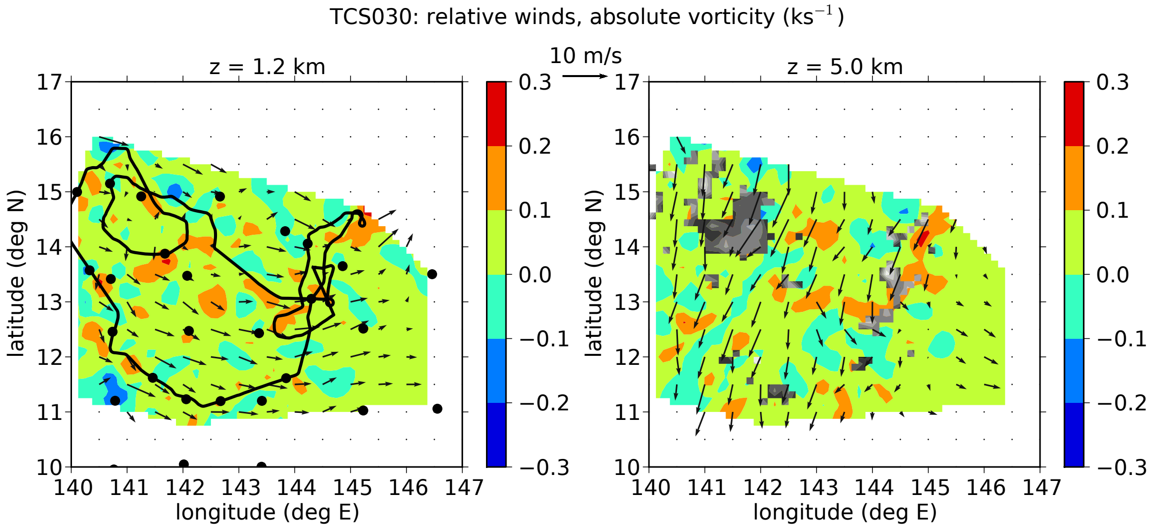

Figure 2: **As in figure 1 except the TCS030 mission. No circulation centers are indicated.**

Figure 3 shows the wind profiles obtained by averaging the analyzed wind data over the domain studied. (For the Nuri 3 case the observational coverage was mostly to the north of the tropical storm center, and the wind profiles are therefore contaminated to an unknown degree by the storm circulation itself. This is less of a problem with the other cases, for which the coverage is more symmetric, which results in approximate cancellation of the storm circulation component.) The interesting result here is that the displacement between the 1.2 km and 5 km centers is approximately normal to the direction of the wind shear, which is from the north-northeast. A similar relationship exists in the second Nuri mission between the shear (now out of the east-northeast) and the displacement between the circulation centers at the two levels (result not shown).

The displacement of the circulation center with height could be thought of as representing a "tilt" in the vortex due to shear. However, the "vortex" at the tropical wave and depression stages of Nuri is more accurately described as a large, amorphous region of vorticity with no well-defined center. A much simpler interpretation of the observed displacement of the circulation center results from considering the interaction of the induced circulation of a broad, non-tilted column of horizontally uniform vorticity with the sheared environmental wind. As figure 4 illustrates, the circulation center of the combined flows shifts to the left of the storm-relative wind at each level. In the case of Nuri 1 the storm-relative wind is from the south at low levels and from the northeast at middle levels, shifting the 1.2 km center to the west and the 5 km circulation toward the southeast by this hypothesis. These hypothesized shifts are consistent with the observed positions of the circulation centers in figure 1. Similar conclusions may be drawn about the positions of the circulation centers at the two levels in the Nuri 2 case (results not shown).

Figures 5 and 6 show the vortex stretching tendency at 1.2 km and 5 km for the first and third Nuri missions. Stretching is produced by deep convective mass flux profiles which increase

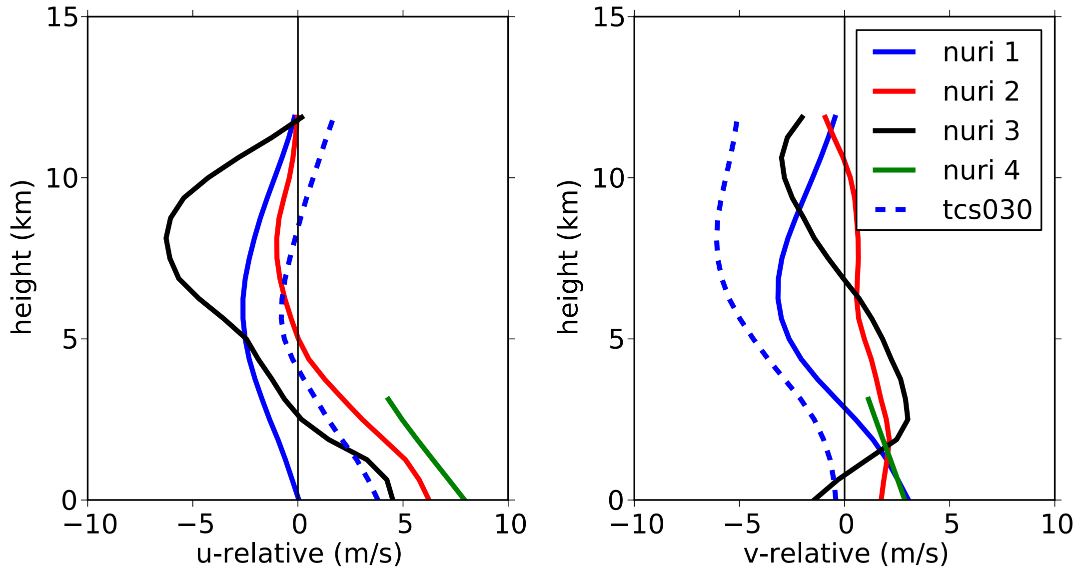

Figure 3: **Storm-relative westerly (left panel) and southerly (right panel) wind components for the four Nuri missions and TCS030.**

strongly with height. Note that as a tropical wave (Nuri 1), stretching regions are scattered over a broad area with no apparent organization. In contrast, at the tropical storm stage (Nuri 3), the stretching is much stronger and is concentrated in a limited region near the center of the circulation. The arrows in these figures represent the advective plus non-advective horizontal fluxes of vertical absolute vorticity. This "flow" is similar to the actual velocity field, since the advective flux of vorticity is the strongest contributor to the total flux.

Figures 7 and 8 show various area-integrated quantities for the first and second Nuri missions. The left panel in each case shows the absolute and planetary circulations around the systems, whereas the right panel shows the integrated vertical mass flux. The center panel shows the individual component and net circulation tendency profiles, obtained from our vorticity budget calculations. The "convergence" tendency is that due to the horizontal convergence of the vertical component of vorticity due to the horizontal flow. The "tilting" tendency is that related to the vortex tilting process, or alternatively to the vertical flux of horizontal vorticity. The "friction" term is due to surface friction, which is assumed to be deposited mainly in the planetary boundary layer. The "net" term is the sum of these three terms.

Mass continuity implies a strong horizontal inflow at levels for which the vertical mass flux increases rapidly with height. Such inflow is associated with strong vorticity convergence and increase in circulation, as is seen in the convergence tendency profiles in figures 7 and 8.

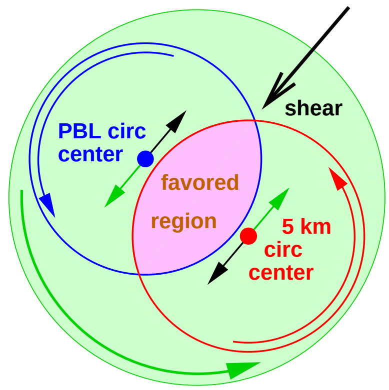

Figure 4: **Interaction of shear (thick black vector) with a broad region of positive relative vorticity (large green circle). The circulation centers in the PBL and at 5 km are located where the system-relative ambient winds at the respective levels (black arrows) just balance the induced circulation from the vorticity pattern (green arrows). The blue and red circles represent the limits of closed circulation streamlines in the PBL and at 5 km. The magenta-colored region of overlap between these circles represents the region where the entire column between the PBL and 5 km is protected from incursions of environmental air.**

The change between the first and second Nuri missions is striking. In Nuri 2 the strongest increase in vertical mass flux with height, and therefore the strongest inflow, occurs at low levels. This inflow causes the low-level, convergence-related circulation tendency in figure 8 to increase drastically over that seen in figure 7, making the net circulation tendency strongly positive in Nuri 2, compared to weakly negative in Nuri 1.

RESULTS

Our analysis of typhoon Nuri and tropical wave TCS030 support the following conclusions:

> Nuri spun up rapidly from a tropical wave to a typhoon in spite of significant environmental shear. TCS030 was subject to similar shear and did not spin up. This difference in behavior was probably related to the existence of a deep and robust closed circulation in the co-moving reference frame (a "pouch") in Nuri at the tropical wave stage and its absence in TCS030. This result supports some of the ideas put forth by Dunkerton et al. (2009).

> The displacement of the center of the Nuri circulation with height is explained as the result of the interaction with shear of a large, wave-associated column of positive relative vorticity. This displacement, though of order 2°-3° between the surface and 5 km in the wave and tropical depression stages, was still small enough for a column protected from environmental incursions to exist through this elevation range.

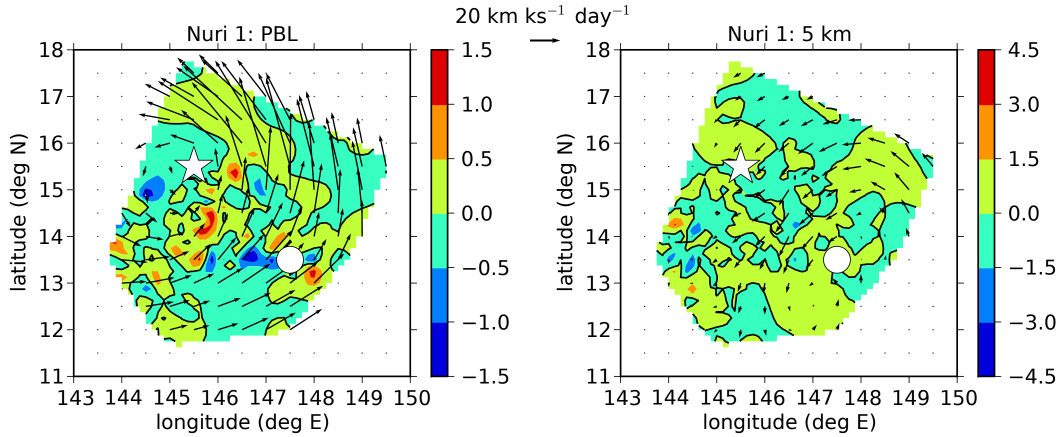

Figure 5: **Stretching tendency (filled contours) for vorticity and total vorticity flux (arrows) in the PBL ($0 < z < 1.2$ km; left panel) and at 5 km (right panel) as calculated from the analyzed wind fields for Nuri 1. The white stars (PBL) and circles (5 km) indicate the PBL storm-relative circulation center and the black contours indicate zero stretching tendency. The vorticity flux has been low-pass filtered with a filter length of 0.5° for clarity of the overall pattern, but the stretching tendency has not.**

> The rapid intensification of Nuri is related to the development of convective mass flux profiles showing a strong increase with height at low levels. By mass continuity this implies strong inflow at low levels and correspondingly strong vorticity convergence. In the case of Nuri 2, this vorticity convergence dominated all other circulation tendency terms at low levels, resulting into the rapid spinup of Nuri into a tropical storm by the following day. The mass flux profile in the non-developing TCS030 case (not shown) was much weaker.

> As Nuri intensified, regions of convective vortex stretching became fewer and more intense, culminating in the formation of a strong central vortex. This suggests the systematic evolution toward fewer and stronger convective systems ("vortical hot towers") as Nuri became stronger.

These results raise an interesting question; what caused the mass flux profiles to evolve from that seen in Nuri 1 to Nuri 2? We suspect that this evolution is largely due to changes in the thermodynamic environment of the convection, i. e., in the humidity and temperature profiles. Preliminary work suggests that these profiles became more humid and more stable as Nuri evolved. This is consistent with the cloud resolving model results of Raymond and Sessions (2007), which show lowering of the elevation of maximum vertical mass flux in convection under these conditions, but additional work is needed to get a good picture of this process in developing tropical cyclones.

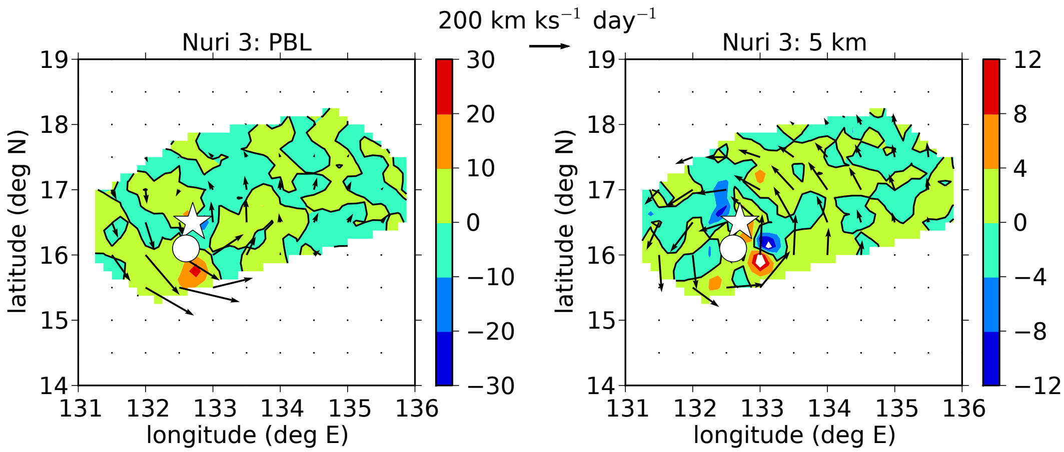

Figure 6: **As in figure 5 except for Nuri 3. Note the change in scales.**

IMPACT/APPLICATIONS

Though we cannot point to immediate applications of this work, in the longer term a clarification of the mechanisms supporting tropical cyclone formation and the role of moist convection in this process should lead to an improvement of cumulus parameterizations in large-scale models and hopefully improved cyclogenesis forecasts.

RELATED PROJECTS

The current project is related to work being pursued under a grant from the National Science Foundation entitled "Cumulus Convection and Large-Scale Tropical Flows". The purpose of that NSF grant is to refine and extend our understanding of the thermodynamic control of convection and to begin to apply these results to a broader range of tropical disturbances. In addition to the Madden-Julian oscillation, we are particularly interested in equatorial Kelvin waves, tropical easterly waves, and the developmental stages of tropical cyclones. TCS-08 results will advance the purposes of this grant and expertise developed under this and previous NSF support will benefit our Office of Naval Research project as well.

We also have NSF support for our role in the PREDICT project with a grant entitled "Vorticity and Thermodynamic Budgets in Easterly Waves – PREDICT Participation". The field program for PREDICT just concluded after obtaining extensive dropsonde data on a number of pre-tropical-depression disturbances as well as a number of non-developing systems. Results from this project should complement and strengthen our TCS-08 results.

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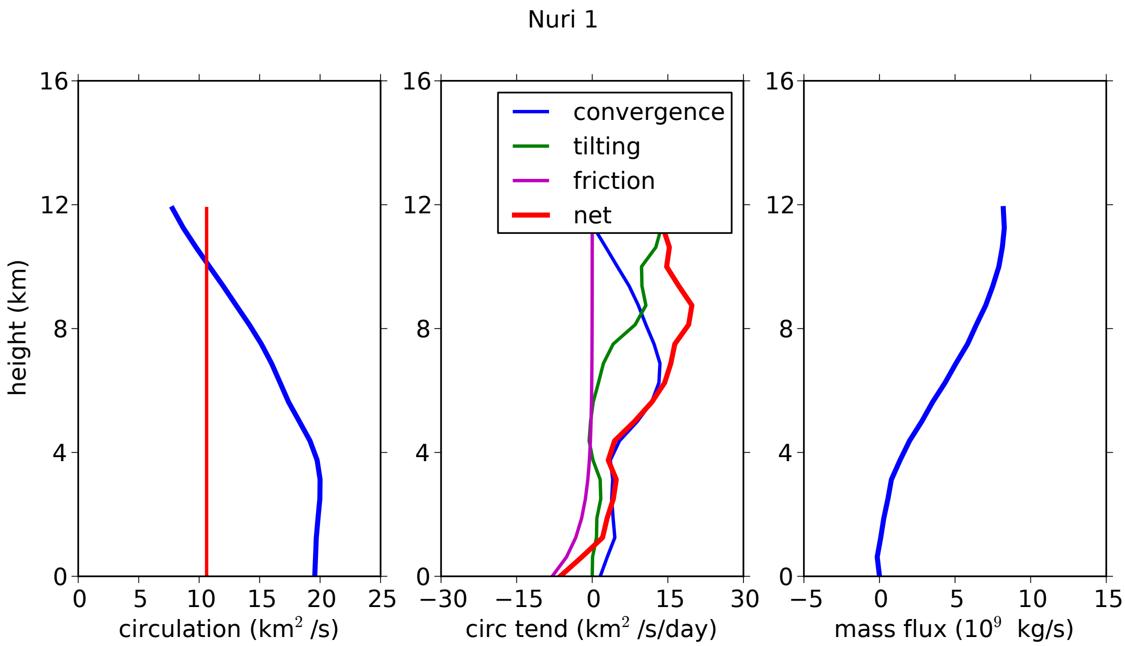

Figure 7: **Nuri 1 vertical profiles integrated over the analyzed region shown in figure 1. Left panel: Planetary (red) and absolute (blue) circulations. Center panel: Contributions to the total circulation tendency (red) due to vorticity convergence (blue), vortex tilting (green), and surface friction (magenta). Right panel: Vertical mass flux profile.**

López Carrillo, C., and D. J. Raymond, 2010: Retrieval of three-dimensional wind fields from Doppler radar data using an efficient two-step approach. *Atmos. Meas. Tech.*, submitted.

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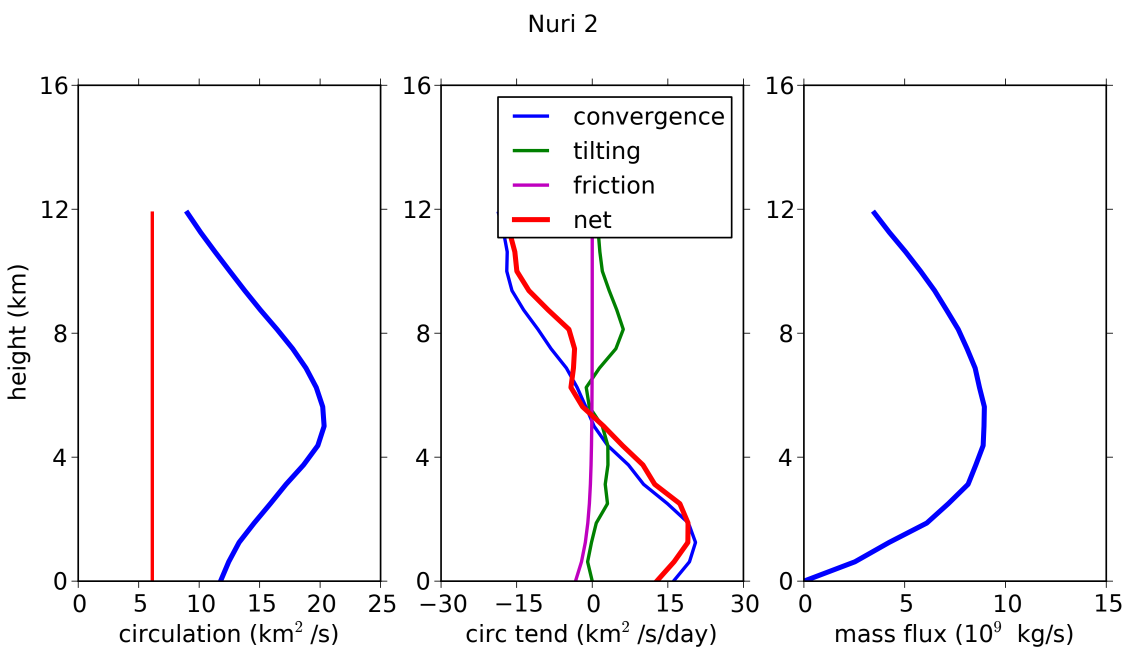

Figure 8: **As in figure 7 except Nuri 2.**